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Direct Fuel Injector Temporal Measurements

by Xiaohua Zhang, Alan Palazzolo, Chol-Bum Kweon, Erwin Thomas, Randall Tucker, and Albert Kascak

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Direct Fuel Injector Temporal Measurements

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14. ABSTRACT

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15. SUBJECT TERMS

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Abstract

The objective of this study is to measure high-frequency, short-duration, actual liquid fuel spray events using a simple photo detector and validate the results with high-speed camera measurements. This paper presents an optical approach for detecting bulk fuel injection's temporal characteristics, i.e. opening delay and duration times. A key component in the measurement system is a commercially available low-cost photo detector which is shown to be highly effective for detecting high frequency, short duration spray events. The paper provides an in-depth discussion of a photo detector based measurement system, a test fixture, and its validation. Test results with a two-stage pulse-width-modulation (PWM) current controlled approach are provided for various operation parameter settings. Its effectiveness is validated by comparing with the results obtained with a high-speed camera.

Introduction

Fuel injectors have a long history in metering fuel in modern engines by either port fuel injection (PFI) or direct fuel injection (DFI). Compared with a carburetor, fuel injectors have more accurate fuel delivering capability, thus giving engineers and technicians more flexibility to optimize engine performance and emissions.

Fuel injectors contain an actuator, pintle (or needle), and nozzle. The most common actuator is a solenoid type with a plunger and spring. Other actuators include piezoelectric and magnetostrictive types. The fuel injector used in this paper is a solenoid-type direct fuel injector. The manufacturing specification is listed in Table 1.

An electromagnetic field is created in the air gap between the stator and pintle (movable plunger type object) as current is applied to the solenoid coil. The pintle tends to close the air gap due to the magnetic force. The magnetic force overcomes the forces (i.e. pressure, spring and contact friction) initially applied on the pintle, and moves the pintle while compressing the return spring to open the nozzle.

Table 1. Direct fuel injector specification [1].

Fuel injector	BOSCH HDEV 5.2
Fuel injector resistance	1.5 ohm
Measured inductance	L = 1.9 mH @ 1 kHz L = 3.9 mH @ 0.12 kHz
Operating pressure	200 bar
Number of holes	6

The essence of optimizing engine performance and emissions is related to precise control of fuel injection timing and quantity. For example, fuel injection usually takes place several degrees before top dead center (TDC) for better mixing before the ignition and a couple of degrees after TDC for enhanced power output for compression-ignition engines.

Figure 1. BOSCH direct fuel injector used in this study.

Injection timing was conventionally calibrated experimentally in an engine bench. In more recent work, the design of experiment and optimization tools has been used for engine calibration, leading to significantly reduced development time. In addition, calibrated and validated software tools have been applied to determine optimal injection timings for better preparation of the local fuel-air mixture before ignition. In one of the software codes, the fuel injection on and off times are determined by a user, e.g. users type in the values $Angle_{on}$ and $Angle_{off}$ (degree) relative to TDC, which indicates the start and stop time of the fuel injection. These values are then converted into t_{on} and t_{off} (milliseconds) based on the engine speed, which further determines the fuel-air mixing time before ignition, thus affecting the combustion process. The t_{on} and t_{off} are eventually programmed into the engine control unit (ECU) under different engine conditions for optimized engine performance and emission.

Ideally, t_{on} and t_{off} are the times when the fuel injection starts and stops. In reality, there is a delay time from the ECU sending command signal to the actual fuel injection called a combined (electronic + hydraulic) delay time. Due to the short time period of the injection, i.e. about 0.3~a few milliseconds, the delay times (which is in the order of a few tenths of a millisecond for advanced solenoid injectors) can have significant effect on the fuel-air mixing time and the following combustion, especially for multiple injections.

Three general approaches have been used to measure injection events: (1) pintle (needle) lift measurement assuming that fuel is immediately injected as the pintle moves [2, 3, 4, 5], (2) dynamic pressure measurement in a tube or a membrane with a specified length and cross-sectional area [6, 7, 8], and (3) direct fuel spray detection using optical methods [9, 10, 11, 12, 13]. These methods are mostly for visualization purpose, e.g. for studying penetration depth and cone angle. High-speed cameras have arrays of photon-sensing devices to capture images. The same principle applies to line-scan cameras, which have only one line of such sensors. The simplified version is a single photo detector, which detects the start and end of injection with significantly reduced price, i.e. the cost of the high-speed camera used in the study is $70,000, a line-scan camera costs about $4000, while the photo detector

system only costs $1. Even though the more advanced methods such as high-speed camera and line-scan camera give more information, i.e. spray structure, than just the on-and-off signal, the photo detector fulfills the purpose of detecting start and end of the bulk spray while the cost of the system is very affordable.

The photo detection system usually contains an emitter and a receiver. The emitter sends out a continuous beam of photons. Without obstruction, the photons impinge on the receiver end and complete the circuit on the receiver side, creating a voltage output. This output is proportional to the quantity of the photons impinged on the receiver. In the fuel spray detecting case, the fuel spray is an obstruction in the path of the light beam. The change of the voltage output indicates the change of the obscurity of the path, which is associated with the fuel injection event.

The previous study made by Szwaja[9] has limited injection frequency because the fuel tends to atomize into vapor cloud around the photo detector after injection. Their system had to run at 2 Hz or less for the cloud to be cleared before the next injection event starts. However, typical injection rate, 5 ~ 67 Hz, is much higher than the test frequency the author was using. The author measured the low frequency injection event with the assumption that it would be the same as the one at higher frequency. This is not necessarily true in real cases. On one hand, the hydraulic waves formed during the opening and closing of the pintle change at different operating frequencies. This leads to shot-to-shot variation at different fuel injection rates. On the other hand, the current to the solenoid experiences subtle changes of its shape due to the capacitor discharge variation at different rates. These two factors together may affect the dynamics of the injector as the injection rate changes. Therefore, further investigation is needed to obtain the injection event data at more realistic operating frequencies. In addition, this previous work did not provide validation of the accuracy of the photo detector approach, in order to justify effectiveness.

The objective of this study is to develop a cost-effective photo detector method, improve the photo detector-based measurement system for injection frequencies up to 100 Hz, and validate the measurement accuracy with the high-speed camera measurements under the same conditions. This technique does not include the measurement of the individual injections at the multihole injector nor its injection rate shape. In other words, only the bulk spray's temporal characteristics can be obtained using this method.

Measurement System

Photo Detector

The photo detector employed for fuel injection temporal measurement is a model H21B1 (Fairchild Semiconductor Corporation) which is shown in Figure 2. The photo detector's electronics properties are listed in Table 2 and its commercially available cost per unit is $0.94. It consists of a gallium arsenide IR emitting diode (emitter) coupled with a silicon

phototransistor (receiver) in a plastic housing. It has 0.889mm (.035′) aperture (the width of the light beam), which should give enough resolution for detecting the time it takes for spray to pass the light path.

The injected fuel travels between the emitter and receiver and blocks the light signal, lowering the quantity of photons impinging on the receiver, thus changing the photo detector output voltage. The circuitry in the present system, as shown in Figure 3, is designed to amplify the output voltage when the photo detector senses a fuel spray.
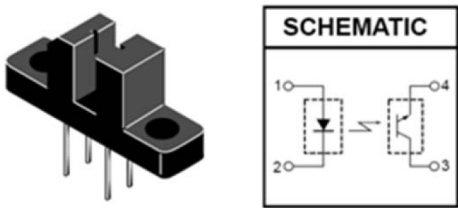

Figure 2. Photo detector for measuring an injector spray event[14].

Table 2. Photo detector's electronics properties.

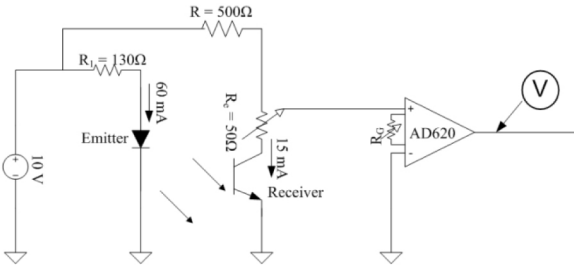| Output configuration	photodarlington
Current – DC Forward	60 mA
Voltage – Collector Emitter Breakdown (Max)	30 V
Turn-on Time	7 μs
Turn-off Time	45 μs

Figure 3. Photo detector drive circuit.

An instrumentation amplifier is used to amplify the photo detector output signal. There is a constant 4V DC offset of the photo detector output. The gain is optimized in such a way that the output voltage V as shown in Figure 3 will experience a 5V jump when a barrier is detected in the light path. The distance between the emitter and receiver ends also has a significant influence on the output signal, and test results showed that 20 mm was the largest allowable separation between the emitter and detector. Beyond this distance, the output voltage does not experience significant change with or without obstruction.

The photo detector bandwidth was tested in-house due to the unavailability of the bandwidth data from the product data sheet. The measurement system required at least 5 kHz to avoid signal aliasing and for detecting the injection as short as 200 μs. A rotating chopper (highest speed at 22,000 rpm with 36 toothed chopper) was used to determine the bandwidth as illustrated in Figure 4. The photo detector output bandwidth was determined to be at least 14 kHz (71.4 μs), which is sufficient to detect typical injection spray event.

The limitation of injection frequency is determined by the response time after the blocking object is removed. This time can be found in Table 2 as "turn-off time". Therefore, the time apart between two injections cannot be less than 45 μs (22 kHz). The minimum injection duration time is determined by "turn-on time" in Table 2, which shows 7 μs is the minimum injection duration time that can be detected by the photo detector circuit. The capability of detecting such a short spray enables the photo detector technique to characterize ultra-high frequency, multi-pulse injection events.

The time resolution of photo detector can be determined by the "turn-on" and "turn-off" times. The opening delay times may be off by at least 7 μs, while the duration times may be 45 μs more than the reality. These errors due to the electronics are insignificant given that they are less than one tenth of their dominant values (400 μs and 750 μs respectively at 500 μs control signal on-time).
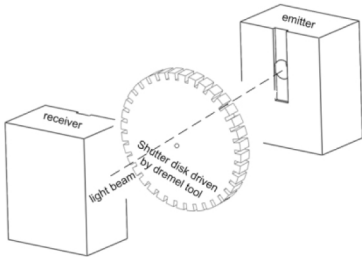

Figure 4. Photo detector bandwidth test arrangement.

Implementation

Effective means to implement this photo detector device were discovered during the development process. The photo detector must be positioned beneath the downward pointed injector nozzle, and its light beam must be positioned close to the nozzle. This close proximity risks direct contact of the spray with the photo detector which may render the device dysfunctional. The high fuel injection pressure also produces an atomized mist which can gradually deposit on the emitter and receiver, producing false indications of spray event. These problems were mitigated by purging the mist away from the emitter and receiver with nitrogen gas. The purging nitrogen pressure varies from 0 to 40 psi. Higher supply pressure injection requires higher purging nitrogen pressure to clear the photo detector path. The effect of the nitrogen purge on the injection spray temporal characteristics should be minimal due to the relatively high injection spray speed compared with nitrogen flow speed. However, the purge of the nitrogen will have effect on spray structures, i.e. spray penetration depth and spray angle, due to the interaction between droplet and flowing nitrogen.

In this study, the ambient pressure inside the spray chamber was near atmosphere. This is different from the real engine chamber condition where higher ambient pressure, thus higher ambient density, is achieved through the compression cycle. There have been studies about the effect of ambient density and temperature on spray penetration depth and spray angle [15, 16, 17]. In this study, however, these ambient parameters' effect on injection temporal characteristics was not taken into

consideration due to the scope of this paper. A further study of using photo detector approach to measure injection temporal characteristics with these ambient parameters as variables should be an interesting topic.

An injector and photo detector holder was designed to incorporate all the features mentioned above: (1) the distance between the emitter and receiver is within 20 mm; (2) the photo detector is positioned close to the injector nozzle; (3) nitrogen gas is continuously purged through channels that lead to the photo detector front face to clear the fuel mist after each spray event. Figures 5 and 6 illustrate the construction and installation of the photo detector based measurement system.
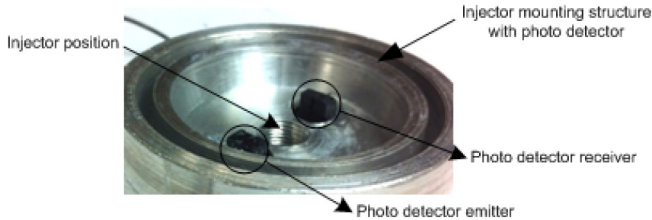
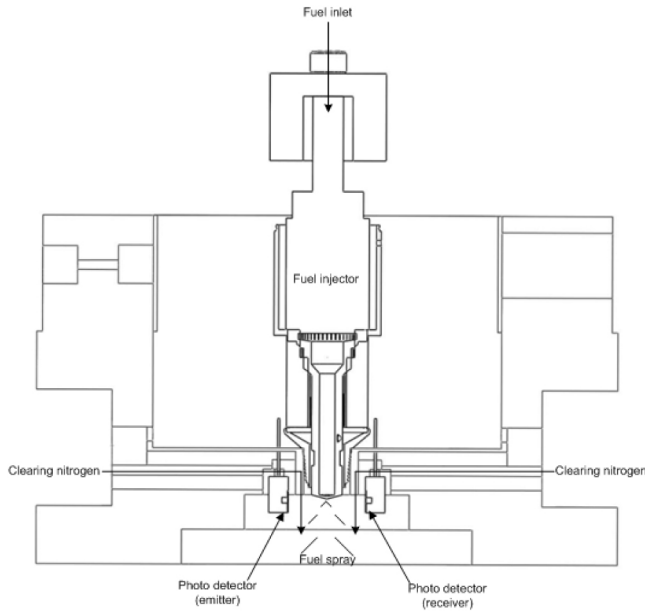Figure 5. Support ring for mounting the fuel injector and photo detector.

Figure 6. Section view of the mounting structure with nitrogen path.

Injector Power Drive System and Data Acquisition System

Fuel injector performance is directly related to its control and power system. Ideally, the fuel injector would function like a switch, i.e. switch on when fuel injection is desired and switch off when the command signal stops. However, the current cannot increase or decrease instantaneously like a switch due to the inductance of the coil. Instead, a certain current increasing or decreasing rate is expected. One would need to apply higher voltage in order to reach the same level of current

faster due to the relationship $V = i \cdot R + L \cdot \dfrac{di}{dt}$, which gives

$$i(t) = \frac{V}{R} \cdot (1 - e^{-\frac{R}{L} \cdot t}) = \frac{V}{R} \cdot (1 - e^{-\frac{1}{\tau} \cdot t})$$

; given the same time constant τ and the same current level i, the time to reach this current is $t \propto \dfrac{1}{V}$. Since the maximum voltage is limited, this unwanted delay due to the inductance becomes the main obstacle for fast switching.

A Pulse-Width-Modulation (PWM) servo amplifier is often used in modern direct fuel injectors. It not only saves power by switching on and off at high frequency, but also is capable of outputting current shapes that accurately follow the input control voltage through feedback circuits built inside. The specification of the PWM servo amplifier used in this study is listed in Table 3.

Table 3. PWM servo amplifier specification

Model	50A20T by Advanced Motion Control
Peak current	50 A
Continuous current	25 A
Supply voltage	40 ~ 190 VDC
PWM Switching frequency	22 kHz

A two-stage power strategy is used to drive the fuel injector. The 1st stage current usually has large peak values and its total on-time is 300 ~ 500 μs. The large peak value is to ensure a fast rising current even though the threshold current may be much lower than the peak value. As we discussed earlier $t \propto \dfrac{1}{V}$, thus a larger supply voltage can achieve a desired current level faster. An advantage of the PWM servo amplifier approach is to regulate the peak current values via the input control voltage, while maintaining the same rise time as the constant voltage source RL circuit case. A 120 VDC power supply was used together with a large capacitor as the power supply to the PWM servo amplifier. The purpose of the 1st stage current is to open the pintle, while the 2nd stage current is to maintain the pintle at the fully open position. The operating pressure force is the major force that the threshold current has to overcome for the 1st stage. This pressure force drops to nearly zero at the pintle fully open position, and steady flow forms at the pintle valve seat. Thus, the 2nd stage current only needs to overcome the compressed spring force, which is much lower than the operating pressure force at the closed pintle position. This permits lower current to be utilized to keep the pintle at its open position for the 2nd stage.

The drive current specification is listed in Table 4. The current amplitude at each stage is chosen to be more than sufficient to operate the injector at 200 atm supply pressure.

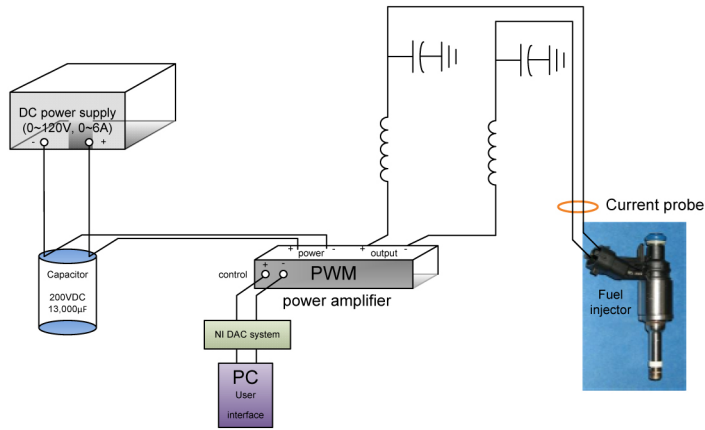| 1st stage peak current	1st stage on-time	2nd stage current	2nd stage on-time
14 A	300 ~ 500 μs	5 A	100 ~ 2600 μs

Figure 7. Injector drive system with PWM servo amplifier.

Figure 7 shows the injector drive system. Injector power drive strategy was selected by varying the 1st stage current and time duration, as well as the 2nd stage current in order to operate the injector consistently with the least power consumption.

Since the focus of this paper is on implementation of the photo detector to measure the temporal characteristics of fuel spray, the power strategy used in this study is only for illustrative purpose. The accompanying paper "Direct fuel injector power drive system optimization" provides the details on how to choose the right power strategies [18].

Hydraulic System

The fuel used in the following experiments was JP-8. However, any liquid fuel type should be a sound substitute in the photo detector system. Different fuel properties, i.e. density, viscosity, vapor pressure, etc., may affect injector actuator response, thus slightly varying the temporal characteristics [19, 20, 21]. Using photo detectors to study the spray temporal characteristics with different fuel properties might be an interesting topic in future.

High pressure nitrogen up to 200 atm was used to pressurize the fuel line to the injector through an accumulator. A gear pump was used to refill the accumulator with JP-8. The injector was contained inside the injector test fixture, which also incorporates the photo detector and clearing nitrogen path. The injected fuel (liquid and vapor phase) was condensed through two Graham condensers and collected at the fuel bucket. The

spray chamber was connected to atmosphere through condenser and liquid trap. Figure 8 shows the entire hydraulic system.
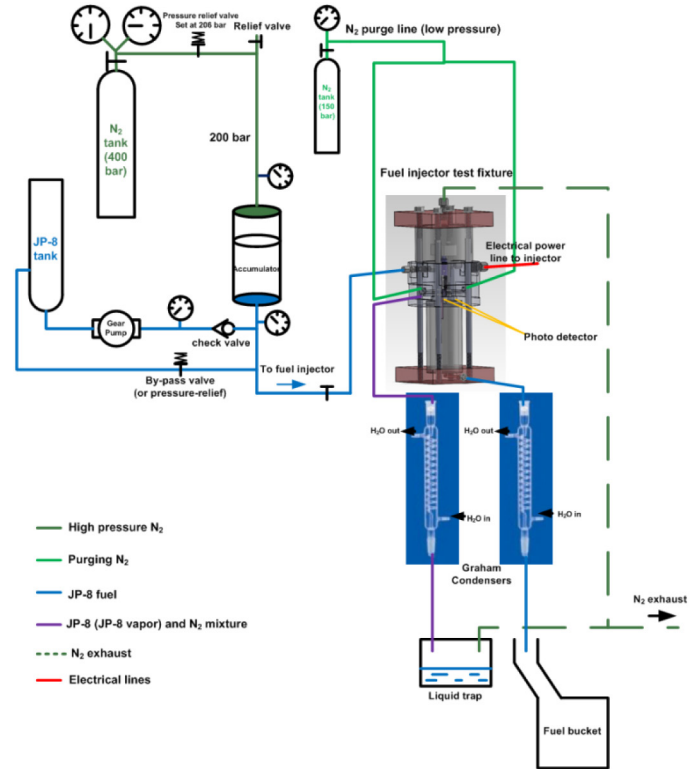

Figure 8. Hydraulic system illustration of the injector test bench.

Results and Discussion

Injector Test Results with Photo Detector System

Figure 9 shows the signals with JP-8 fuel, injector supply pressure of 200 atm and 1 ms total injection signal on-time (1st stage-0.4 ms at 14 A peak current and 2nd stage-0.6 ms at 5 A holding current) case. The sampling rate of the data acquisition system was 80 kHz for each of the 3 channels employed. The black dashed line shows the two-stage control voltage input to the PWM servo amplifier. The blue solid line is the current from the PWM servo amplifier to the fuel injector. The red dash-dotted line is the photo detector output signal (in volts). As previously mentioned, the high voltage (approximately 9 V) indicates a light barrier (fuel spray in this case) being detected, and the low voltage (4 V) indicates there is no barrier (no fuel spray in this case) being detected. The well defined profile of the photo detector output signal was maintained by purging with nitrogen gas to prevent the fuel spray mist from depositing on the emitter and detector. Removal of the purge gas would result in significant deterioration of the photo detector signal. Figure 10 shows a zoomed-in plot of the first injection event of Figure 9.
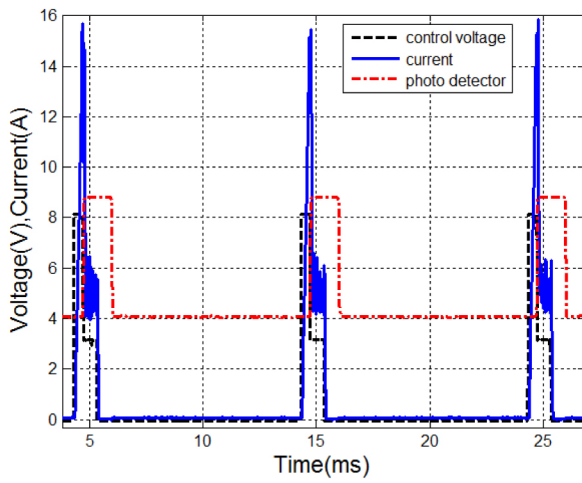
Figure 9. Control voltage, current and photo detector signals for a two-stage PWM amplifier powered direct fuel injector spray event at 100 Hz injection rate under 200 atm fuel pressure.
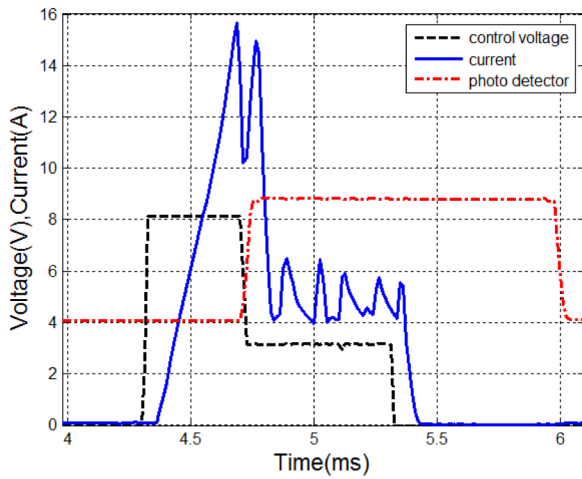

Figure 10. Zoomed-in view of Figure 9 showing signals for a single injection event.
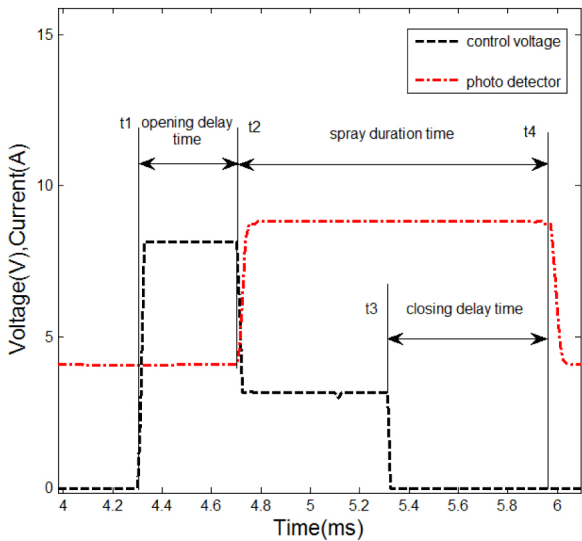

Figure 11. The spray temporal definitions.

The time traces of the acquired signals provide a means to measure the injector valve opening time, injection duration time, and injector valve closing time. For example, Figure 11 shows the injector valve opening time (t_2-t_1) which is the time delay between the control signal from the Labview system and the actual spray coming out from the nozzle sensed by the photo detector. The injector valve closing time (t_4-t_3) is the time delay between the closing signal and actual closing of the pintle, plus the delay between actual closing of the pintle and the photo detector off signal. The injection duration time (t_4-t_2) is the photo detector high time.

According to the spray temporal definitions in Figure 11, the spray shown in Figure 10 has the temporal parameters listed in Table 5. This delay time is a combined delay time of electronic and hydraulic delays.

Table 5. Spray temporal characteristics of the injection event in Figure 10 at 1 ms control signal on-time.

Opening Delay Time	Spray Duration Time	Closing Delay time
[ms]	[ms]	[ms]
0.40	1.28	0.68

Figure 12 compares injection events with different control signal on-times under the test conditions listed in Table 6. Table 7 lists the temporal characteristics of the injection events from Figure 12.

Table 6. Test conditions

Control signal on-time	0.5~2 ms
1st stage peak current	14 A
1st stage on-time	0.4 ms
2nd stage current	5 A
2nd stage on-time	0.1~1.6 ms
Injection rate	100 Hz
Supply pressure	200 atm (gauge pressure)
Ambient pressure	1 atm (absolute pressure)

Spray temporal characteristics at lower pressures (from 20 atm to 180 atm with 40 atm increment) were also measured. It turned out the variations of opening delay and spray duration times at different pressures were small, i.e. opening delay times varied from 0.39 ms to 0.43 ms and spray duration times varied from 1.25 ms to 1.31 ms for 1st stage-0.4 ms at 14 A peak current and 2nd stage-0.6 ms at 5 A holding current, from 20 atm to 200 atm supply pressures. Therefore, only 200 atm supply pressure cases were presented in this paper.
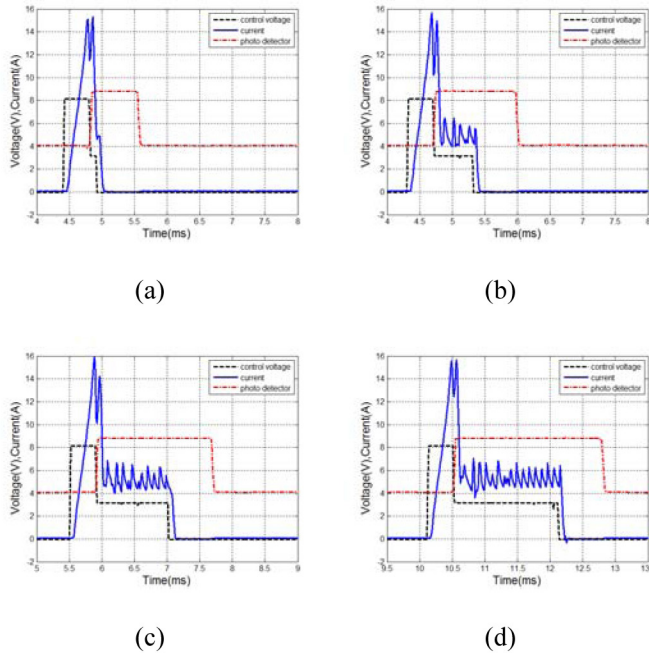
(a)　　　　　　　　　　(b)

(c)　　　　　　　　　　(d)

Figure 12. Injection events with different control signal on-times at 100 Hz injection rate under 200 atm fuel supply pressure.

Table 7. Spray temporal characteristics with different control signal on-times from Figure 12.

Control signal on-time	Opening delay time (ms)	Duration time (ms)	Closing delay time (ms)
0.5 ms	0.40	0.75	0.65
1 ms	0.40	1.28	0.68
1.5 ms	0.40	1.78	0.68
2 ms	0.40	2.28	0.68

Injector Test Results with High-Speed Camera System

A high-speed camera was used to capture the injection events under the same conditions as listed in Table 6, in order to validate the results with the photo detector. The high-speed camera employed in this study was the Photron SA3. Table 8 lists its specification.

A different spray chamber was specifically made for high-speed camera system. This chamber provided optical access to the spray. Other than that, all parameters including nitrogen purge and ambient pressure were the same as the previous set-up for photo detector system.

The camera was triggered using the same signal to trigger the fuel injector from Labview DAQ system. This gives us a time reference of the pictures taken by a high-speed camera with respect to the injector control signal. Figure 13 shows the frame-to-frame photos of the 1ms total control signal on-time case at 10,000 fps.

Table 8. High-speed camera used in this study.

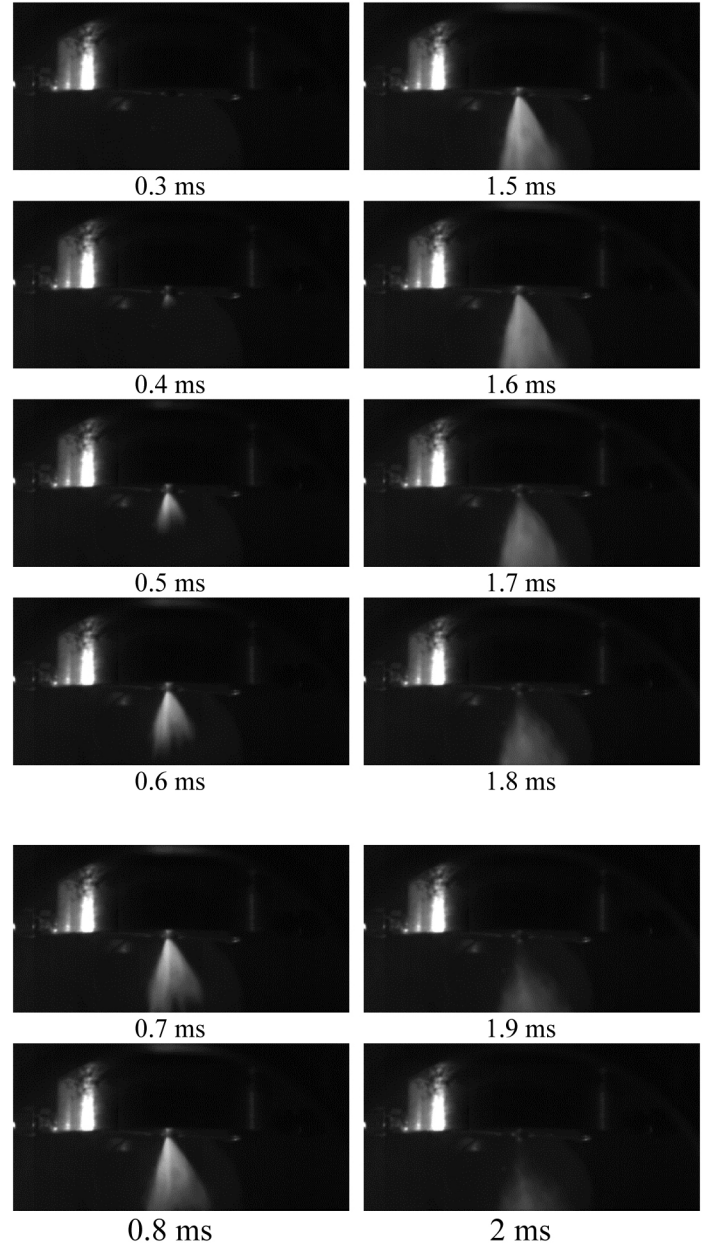| Model	Photron FASTCAM SA3
Max. frame rate	60,000 fps
Frame rate in the study	10,000 ~ 30,000 fps
Resolution in the study	512 x 256 pixels at 10,000 fps 128 x 128 pixels at 30,000 fps
Trigger-type in the study	TTL triggered

Figure 13. Frame-to-frame photos during one injection event with 1 ms control signal on-time at 100 Hz injection rate under 200 atm supply pressure.

Validation

The temporal characteristics of the fuel spray were measured with both the photo detector method and high-speed camera method. Table 9 compares the opening delay, duration and closing delay times under the test conditions listed in Table 6. Findings from both methods illustrate very close results on fuel spray temporal characteristics.

Table 9. Fuel injection temporal characteristics comparison with high-speed camera (HS) and photo detector (PD) methods under the same test conditions.

Control signal on-time	Opening delay time (ms)		Duration time (ms)		Closing delay time (ms)	
	HS	PD	HS	PD	HS	PD
0.5 ms	0.4	0.40	0.7	0.75	0.6	0.65
1 ms	0.4	0.40	1.3	1.28	0.7	0.68
1.5 ms	0.5	0.40	1.7	1.78	0.7	0.68
2 ms	0.4	0.40	2.3	2.28	0.7	0.68

Conclusions

The fuel spray temporal characteristics are important for improving engine performance and emissions control. This paper presents an effective and inexpensive means for measuring the injector temporal characteristics using a photo detector. Injector temporal characteristics such as opening delay time, closing delay time and injection duration time were obtained from the measured photo detector signal. A detailed description was provided for the photo detector circuit, implementation, injector power drive, data acquisition system, and hydraulic system. Also, the direct fuel injector test results were presented using a two-stage PWM current controlled approach. The results presented here are representatives of a vast amount of similar data taken under different operating conditions. In summary, a high-speed camera was used as an alternative way to measure the spray temporal characteristics; and overall, excellent agreement was obtained between the two measurement approaches.

This paper demonstrates that the developed photo detector system is accurate in detecting the spray temporal characteristics at injection rates up to 100 Hz under 200 atm supply pressure. The photo detector method is a cost-effective approach to obtain the spray temporal characteristics such as opening delay, duration and closing delay times. However, in order to study more sophisticated spray characteristics such as spray pattern, rate shape etc., other visualization tools with a high-speed camera system will be more appropriate.

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